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FIELD TESTING SYNTHETIC PREDATOR ODORS FOR ROOF RATS (*Rattus rattus*) IN HAWAIIAN MACADAMIA NUT ORCHARDS

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Abstract—Field trials were conducted to determine whether the synthetic predator odors 3,3-dimethyl-1,2-dithiolane (DMDIT) and (*E*,*Z*)-2,4,5-trimethyl-Δ^3-thiazoline (TMT) were effective at eliciting a behavioral response in wild roof rats (*Rattus rattus*). The study site was a Hawaiian macadamia nut (*Macadamia integrifolia*) orchard with a recent history of roof rat feeding damage. The synthetic predator odors were encapsulated in urethane devices secured to tree branches. Mark–recapture data from live-trapping of rats and radio telemetry location data were used to assess behavioral responses of rats to the predator odors. Mark–recapture data indicated that DMDIT and TMT had no effect on capture numbers, reproduction, or body weight of rats. There was some indication that distribution of captures and number of locations relative to treated trees in TMT areas were less than in controls, but this pattern was not significant. The predator odors had no effect on home range or median distance from center of activity (MDIS) of rats as measured by telemetry. There was a trend of increasing values of MDIS on TMT areas in session 1 but not session 2. Overall we could not detect significant differences or consistent trends in responses of rats to DMDIT or TMT in these field trials.

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INTRODUCTION

The roof rat (*Rattus rattus*) occurs in a wide variety of habitats throughout the state of Hawaii. Its reputation as an adaptable generalist is apparent on this Pacific island by its presence in wooded gulches and forests, agricultural crops, and human structures (Tomich, 1986). *Rattus* species have a history of rapid colonization following their initial introduction to many Pacific islands (Atkinson, 1985; Buckle and Fenn, 1992). *Rattus* damage to the native flora and fauna as well as to food crops and food storage areas has been well documented (Stone, 1985; Tomich, 1986; Buckle and Fenn, 1992; Lund, 1994). Besides posing a risk to native fauna through direct consumption (i.e., plants, bird eggs, insects), rats are also capable of out-competing other animals with similar food sources (Clark, 1980). The roof rat has contributed to the rapid decline in native bird species on the islands, as this is the only rodent species that regularly utilizes tree canopies (Atkinson, 1985; C. P. Stone, personal communication).

The detrimental effects of rat populations on Hawaii's threatened flora and fauna are causing concern. Various agricultural growers are also concerned about feeding damage by rats. Sugarcane, macadamia nut, and coffee orchards have been experiencing rodent damage problems for several years in Hawaii (Tomich, 1986; Tobin et al., 1990, Tobin, 1992; Sugihara et al., 1995). Research into methods to control rats has been extensively investigated by the National Wildlife Research Center (NWRC) Hawaii Field Station and the Hawaiian Sugar Planters' Association.

Past attempts to control roof rat numbers in site-specific areas with toxicants have met with limited success. The capacity of *Rattus* spp. to withstand rodenticide poisoning attempts can be attributed to their neophobic nature, physiological resistance, social structure, and high reproductive rate allowing rapid reinvasion (Prakash, 1988). Other factors contributing to their resiliency in the Hawaiian Islands are their ability to breed year round combined with abundant food sources.

In previous field studies, predator odors were effective in the management of various small mammal species (Sullivan et al., 1988a–c). Field trials with predator odors were usually preceded by smaller-scale studies, such as an arena or pen trial, to initially determine if the animal of concern would respond. Once a desired response was observed, a field trial would then be suggested or performed. To date, most studies investigating predator odors have focused on mammals native to North America. The promising results in many of these

studies suggest a similar approach may provide a management technique for the roof rat in Hawaii.

Laboratory studies have indicated that rats display a fear response when exposed to synthetic predator odors (Vernet-Maury et al., 1984, 1992). The laboratory trials performed prior to this study (Burwash et al., 1998) indicated that the most promising odor for eliciting an avoidance behavior in the Hawaiian roof rat was 3,3-dimethyl-1,2-dithiolane (DMDIT). (*E*,*Z*)-2,4,5-Trimethyl-Δ^3-thiazoline (TMT) and 4-mercapto-4-methylpentan-2-one (MMP) also seemed to produce an avoidance response in the laboratory trials. However, of these two latter compounds, TMT was selected for field testing as it was also the odor that generated the greatest fear response in Wistar lab rats (Vernet-Maury et al., 1984) and wild-caught Norway rats (*R. norvegicus*) (Vernet-Maury et al., 1992).

Tobin et al. (1996) used radio telemetry to examine roof rat movement patterns within a macadamia orchard. Most of the rats den underground in the porous lava substrate or build nests from leaf clippings in the tree canopy. Rats in the orchard have a definite nocturnal feeding schedule with the greatest number of animals leaving their den sites by 23:00 hr. Lunar cycles and rainfall did not seem to affect this feeding pattern. Tobin et al. (1995) found that roof rats avoid traps scented with mongoose urine and feces in field trials, suggesting that the potential for odor avoidance exists.

Based on the laboratory results of Burwash et al. (1998) and other small mammal field study results, we predict that roof rats will avoid predator odors in the field. This study was designed to test the hypotheses that predator odors would: (1) reduce the number, incidence of breeding, and body weights, of roof rats captured; (2) increase the mean maximum distances moved (MMDM) between subsequent captures (mark–recapture) and median distances from center of activity (MDIS) (telemetry) for roof rats; (3) increase the home range size of roof rats; and (4) reduce the proportion of roof rat locations in treated trees.

METHODS AND MATERIALS

The effectiveness of predator odors at producing a response in the roof rat was determined with mark–recapture and radio telemetry techniques. Many studies have also gathered useful information on changes in small mammal populations with mark–recapture techniques (Krebs, 1966; Ritchie and Sullivan, 1989; Sullivan, 1990). Research specific to the roof rat has used live-trapping techniques as well as radio telemetry analysis (Chin, 1983). The design and sampling methodology used for our study were based on previous mark–recapture studies, and a pilot field trial was also conducted to test the radio transmitter collars and recapture success with various baits. The field study was conducted in two sessions based on the battery life of the radio transmitters: session 1 from June

to August 1994 and session 2 from September to December 1994. The radio telemetry procedure remained the same for both sessions; however, the mark–recapture methodology was modified slightly between sessions as discussed below.

Study Site. The study site was a 999-ha macadamia nut orchard located 15 km south of Hilo in the state of Hawaii. The orchard was on the windward side of the island of Hawaii where rainfall was substantial (> 1500 mm/yr) and the general topography relatively flat. The majority of the orchard was comprised of ~25-year-old macadamia trees of different varieties. This varietal mix is primarily for pollination purposes. Orchard soils were volcanic with a 0.3-m layer of crushed lava on the surface providing the substrate in which the macadamia trees were planted. The porous nature of the lava beneath this crushed layer provided rats with an extensive tunnel network easily accessible through many openings to the surface. Vegetative ground cover throughout the orchard was minimal as a result of the regular use of herbicides and manual clearing of leaves. The orchard was laid out in blocks (mostly rectangular) separated by gravel access roads on all sides and Norfolk Island pine tree (*Araucaria heterophylla*) windbreaks on at least two sides of each block. These windbreak areas had a very deep duff layer composed of fallen debris and orchard trimmings that provided another denning area for rodents.

This orchard was chosen to test the predator odors based on the recent history of rodent damage recorded in the macadamia orchard (Tobin et al., 1993) and the relative homogeneity of the orchard. This homogeneity provided a large area of very similar blocks in which to replicate treatments. The blocks were composed of the same tree variety ratio (variety 660, 86%: 508, 9%: 212, 5%) and trees were also of similar age (20–25 years), height (8–10 m), and density (240 trees/ha). Three 20-ha blocks were relatively flat and each block was separated by at least 200 m. Each of the three blocks was divided into two 4-ha rectangular (160 × 250 m) grids. This allowed the study to focus on animals living primarily within the blocks and to avoid those individuals utilizing the windbreaks. Each grid was at least 20 m from the road edge and at least 300 m from the adjacent grid in the same block. As the trees were planted in a grid layout (6.5-m × 6.5-m spacing), specific row and tree locations could be assigned to every tree.

This six-month study was separated into two periods: session 1 from June 13 to August 31, 1994, and session 2 from September 19 to December 14, 1994. For both sessions, pretreatment information was gathered for both the mark–recapture and telemetry information.

Mark–Recapture. In session 1, 100 live-traps (80 Hagaruma, 20 Tomahawk) were used on each grid with placement on every three to four trees per row on every other row pair within each 4-ha grid. Traps were placed on large

lateral branches 1–2 m above ground because previous live-trapping had greater capture success at this location. Placing the traps on the ground tended to capture more mongoose, and those that did capture rats on the ground had increased trap deaths as a result of mongoose predation. All traps were cleaned prior to use and were secured to the branch with nylon twine and rubber bands.

Prebaiting was carried out three days prior to the first trap day of a given trapping week to allow animals to become familiar with taking bait from the traps. This was accomplished by locking open the traps and placing a coconut chunk smeared with peanut butter inside. On the initial trap day, the traps were rebaited and set during the day, left open throughout the night, and checked the following morning. Each trapping week was comprised of three nights of trapping following prebaiting, with trapping taking place every three weeks.

All captured animals were identified to species and marked with an individually numbered ear tag. Color of pelage, sex, weight, and breeding condition (males: scrotal/abdominal; females: perforate/nonperforate and pregnant/not pregnant) were recorded for each animal. An open-ended mesh net-bag with a rope cinch was used to handle each animal for data collection and ear-tagging.

The only mark–recapture data analyzed were those from session 1 as the design in session 2 yielded too few captures to provide a worthwhile comparison. As the numbers of trapped animals were quite variable on each grid and the duration of trapping was limited to five weeks in session 1, open population estimates were applied with caution. Information on composition of rat populations was gained, however, and this provided some useful insight about changes within the captured populations.

In session 2, the above mark–recapture design was used to collar the animals, after which the trap layout was modified. Because of the low number of traps in treated areas in the first session, the design was modified to focus trap placement in treated trees for session 2. Once the areas to receive treatment were determined (see odor placement section), 10 traps were placed within the treated area and trapped on the same schedule and procedure as in session 1.

Radio Telemetry. Roof rats were initially captured in live-traps in each of the six study grids with the session 1 mark–recapture design. Only adult rats were used for telemetry to maintain a similar age class and sufficient sample size. To ensure that radio-collar weight would have minimum effect on normal behaviors, no animals under 90 g were used for radio telemetry. Six animals (three males and three females) were initially radio-collared on each grid. The animals were anesthetized with a general anesthetic (Metofane) by placing the individual into a sealed plastic container lined with anesthetic-treated ($\sim$ 10 ml) cotton. Within 5–10 min the animal would be sedated enough to handle safely. The individual would then be processed as in the mark–recapture procedure, and fitted with a radio transmitter neck collar (Holohil PD-2C). Before releasing

the animal, the transmitter signal would be checked and the animal placed back into the trap to recover. Usually 10–15 min following the collaring, the animal would fully recover and be released at the point of capture.

As roof rats are primarily nocturnal, most of the telemetry locations were taken during the night. A telemetry week consisted of four days of locating animals with each telemetry day comprised of one day location (12:00–17:00 hr) and three night locations (19:00–21:00; 21:01–23:00, and 23:01–01:00 hr). This design was based on the number of active radio-collars and the number of observers available. An observer was equipped with a headlamp, a portable radio receiver (Custom Electronics of Urbana Inc. or Wildlife Materials Inc.) and a hand-held yagi antenna (Wildlife Materials Inc.) to locate radio-collared rats. During an individual's location, the animal would be tracked to a single tree with its location either above or below ground determined. The specific information recorded was: observer, date, time, receiver, tuning and signal strength, location (tree/underground/surface), activity (moving/stationary), visual confirmation (yes/no), and general weather conditions (wind, rain, cloud cover, lunar phase). A shortened data label would then be transcribed onto flagging tape and secured to the appropriate tree. At the end of the four-day telemetry week, the exact location (row and tree label) for each flag was determined and recorded before flag removal.

During each telemetry night, the order in which grids were sampled and specific rats tracked was systematically shifted during each 2-hr location period. This would ensure that individual rats were not always being located at the same point within each 2-hr period.

Predator Odor Semiochemicals. The chemical compounds to be tested as repellents were originally derived from predator species, commonly from the anal scent gland, urine, or feces. The compounds have generally been identified either from extracts of these secretions or from the volatiles that emanate from them. The components believed to have semiochemical activity were prepared synthetically, albeit as racemates. The synthetic odor was encapsulated in a release device (usually PVC or urethane) to control release rates and protect the chemicals from excessive exposure during field use (Sullivan et al., 1990). The synthetic odors were synthesized by Industrial Research Limited, New Zealand, and Phero Tech Inc., Delta, British Columbia, Canada, then encapsulated in release devices by Phero Tech. A list of the odors, an abbreviation, and their original source are given in Burwash et al. (1998). The DMDIT (3,3-dimethyl-1,2-dithiolane) devices were loaded with 8 mg of active ingredient in a 3-cm urethane device, while TMT [(*E*,*Z*)-2,4,5-trimethyl-Δ^3-thiazoline] devices were loaded with 10 mg of active ingredient in a 6-cm urethane device. The difference in concentration of active ingredient was a result of the amount of synthetic chemical available at the time of the study. As the release devices had an expected field life of three weeks, they were replaced once, after the third week

following treatment application, within each session (six treatment weeks per session).

Experimental Design. Each treatment (DMDIT, TMT, and control) was replicated twice and randomly assigned to the six grids. The application of the treatment was focused in areas specific to individual animals rather than in a broadcast area design. This was decided primarily because of the reliable individual movement data available with the telemetry procedure. We were also limited by the number of odor repellents available and personnel to apply the treatment. Focusing on the individual animals allowed assessment of whether individuals shifted their activity in response to placement of the semiochemicals.

After two weeks of pretreatment telemetry locations, specific areas to be treated were determined. Every animal on a grid would receive the same treatment odor even though the treated areas were not continuous over the entire grid but concentrated in specific areas for each animal. This was to prevent any possible contamination of different treatments within a grid. The design in session 2 was modified following the results from session 1.

In session 1, treated areas were composed of nine adjacent trees within an individual rat's weekly home range area, based on frequency of locations during the pretreatment period. The general shape of the treated area was a three-tree by three-tree square. However, due to missing or dead trees, this shape often varied. To maintain consistency in the treated areas, the treatment trees had to be adjacent to at least one other treated tree.

The predator odors were applied by placing a coated wire through a hole in each repellent device and twisting the wire ends to form a loop. Flagging was then used to secure the device to tree branches. Each treated tree received eight odor devices placed at varying heights (2–4 m) throughout the canopy. Their location was also dispersed relative to the main trunk of the tree. Generally, four devices were placed distal to the trunk and four were placed proximal, at variable heights above ground. Feeding by rats was often localized, as indicated by gnawed shells and husks found in flat pocket areas at the base of large branches. These locations and obvious runway areas (along larger branches) were treated with repellent devices. In session 1 there were 72 devices per area (per radio-collared rat).

The schedule was designed such that telemetry weeks occurred on the first and third week following initial treatment application and, following reapplication, mark–recapture trapping took place in the weeks between telemetry sessions.

After mapping the results from session 1, it was apparent that the treatment area was quite small relative to the individual's weekly home range, which often led to the rats avoiding the "treated" (marked but not treated) trees on the control grids. During session 2 we expanded the treated area to 16 trees and increased the number of odor devices placed in each tree to 12 [192 devices per

area (per radio-collared rat)]. A further modification of the application was to place four of the 12 devices around the trunk at a height of ~0.5 m.

This session was also divided into two treatment periods and the first period (session 2, treatment 1) used the same treatment designation as in session 1. Following two weeks of posttreatment telemetry, the semiochemicals were removed. After a week delay, the second period (session 2, treatment 2) was initiated with a pretreatment telemetry week followed by two weeks of post-treatment monitoring. For the second treatment, semiochemical applications were systematically shifted so that each rat received a different treatment for session 2, treatment 2. The design was balanced so that each treatment 1 group would be divided so that each half would receive different semiochemicals for treatment 2. The intent was to observe any trends in individual response to a new semiochemical treatment.

Statistical Analysis. For the mark–recapture data, comparisons in the number and composition of the captured individuals were generated. The number of captures were totaled by week and separated into proportion of recaptures for comparison. Comparisons were made with the actual capture information per unit effort, and other population parameters, by using randomization testing (RANDMIZE program) (Manly, 1990). Randomization techniques are designed for detecting nonrandom change in studies with little or no replication of experimental units and for paired time-series data from individual treatment and control systems (Carpenter et al., 1989). This methodology is not bound by the assumptions of parametric statistics (random sampling, normally distributed populations, and equal variances) as the technique determines the error distribution of its test statistics by randomly reordering the data set (Carpenter et al., 1989; Manly, 1990).

Mark–recapture data were also used to compare capture success within specific treated and untreated areas (capture success within/adjacent to treated trees). This information could also be compared to results from radio telemetry techniques. These data were grouped among treatments because of the low number of traps within or adjacent to treated areas.

The number of recaptures by individual was insufficient to provide a meaningful home range estimate from the mark–recapture data. Where sufficient replication existed, analyses of variance (ANOVA) were conducted to compare between treatments by trapping week.

We calculated the minimum area convex polygon (MCP) for each radio-collared rat to estimate its weekly home range size and median distance from center of activity (MDIS). MDIS was calculated as the median distance of all locations for an animal from its center of activity (mean x and y coordinates of all locations) (SAS Institute Inc.), MCP was calculated with McPaal Microcomputer Programs for the Analysis of Animal Locations (Stuwe and

Blohowiak, 1989). In order to calculate home range estimates, a minimum of 14 locations was needed based on a prestudy plot of home range size versus number of locations.

We also calculated the proportion of telemetry locations in treated trees from the total number of in-tree locations. The capture success relative to treatment areas was determined by considering the proportion of captures in traps located within or adjacent to (defined as within 1 adjacent tree) treated areas. This information should indicate whether an individual is selecting specific trees within its weekly home range.

Separate two-way repeated-measures ANOVAs for the telemetry variables were performed to compare between pre- and posttreatment and between treatments. Sex was grouped, as previous telemetry work in this orchard found no difference in home range estimates between sexes (Tobin et al., 1996b). All ANOVAs were conducted with alpha (α) set at 0.05. To make multiple comparisons, Duncan's multiple-range test was used with an experiment-wise error rate of 0.05 (Saville, 1990).

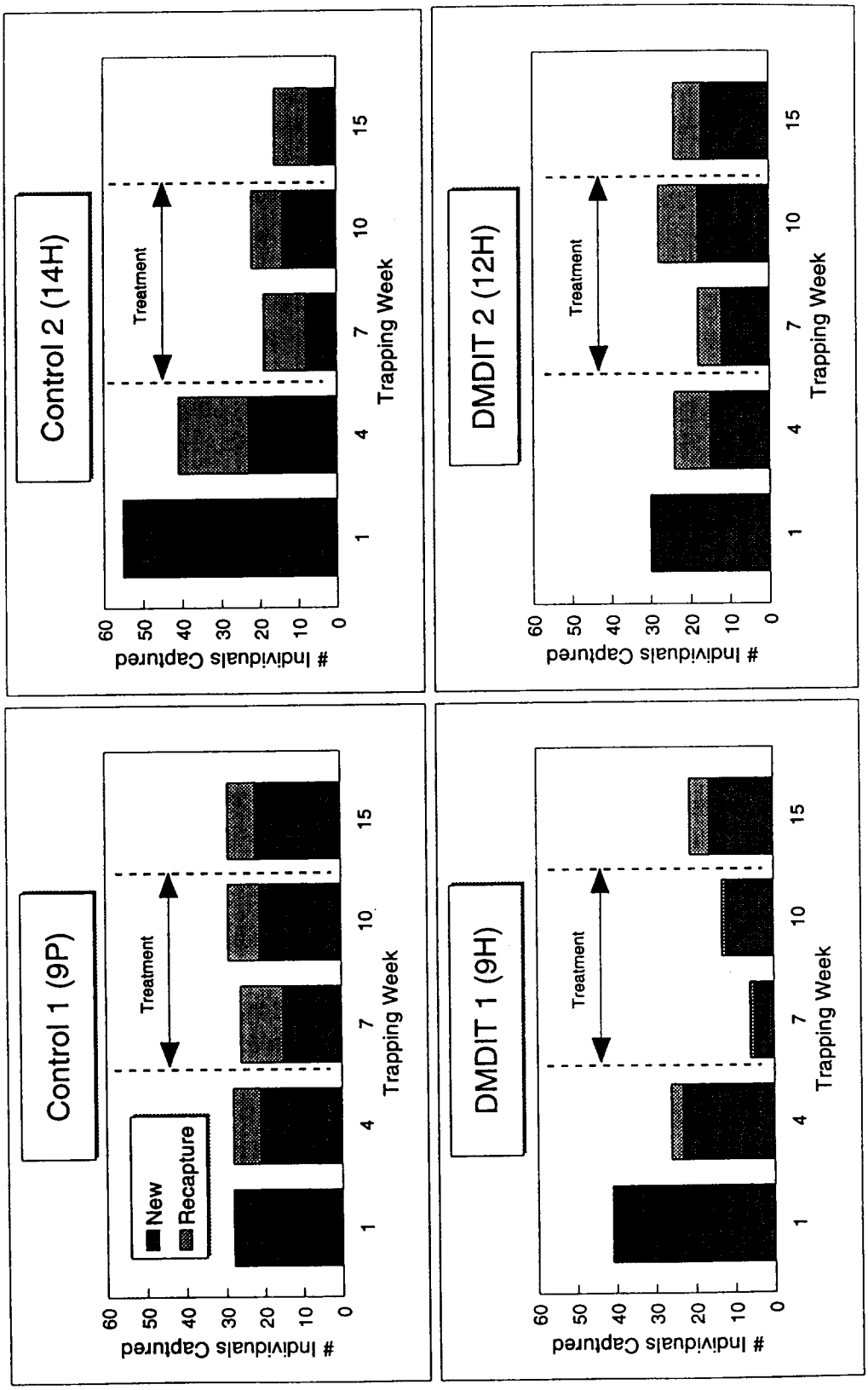
RESULTS

Mark–Recapture. Total number of captures for a trapping week ranged from 5 to 55 individuals. The number of captures and recaptures by grid is displayed in Figure 1. There was a balanced sex ratio for all populations throughout the study. Overall, 582 individual roof rats were captured a total of 1089 times during five weeks of live-trapping. By treatment, 214 roof rats were captured on the control grids, 189 captured on the DMDIT grids, and 179 captured on the TMT grids.

The relative capture data were tested through randomization to compare capture numbers per 300 trap-nights between treatments and between pre- and posttreatment. There were no nonrandom differences in capture numbers of roof rats in pairwise comparisons of controls and DMDIT treatments (two-tailed, $P = 0.47$), controls and TMT treatments (two-tailed, $P = 0.47$), or DMDIT and TMT treatments (two-tailed, $P = 0.74$).

The number of males in breeding condition did not change following treatment application (Figure 2). Randomization testing revealed no nonrandom differences in number of scrotal males captured for pairwise comparisons of controls and DMDIT treatments (two-tailed, $P = 0.71$), controls and TMT treatments (two-tailed, $P = 0.20$), and DMDIT and TMT treatments (two-tailed, $P = 0.50$).

There was no significant difference in the average weight of male roof rats between control and treatment grids during the pretreatment weeks (ANOVA,


Control 1 (9P)
Control 2 (14H)
DMDIT 1 (9H)
DMDIT 2 (12H)
New
Recapture
Treatment
Individuals Captured
Trapping Week
0
10
20
30
40
50
60
1
4
7
10
15

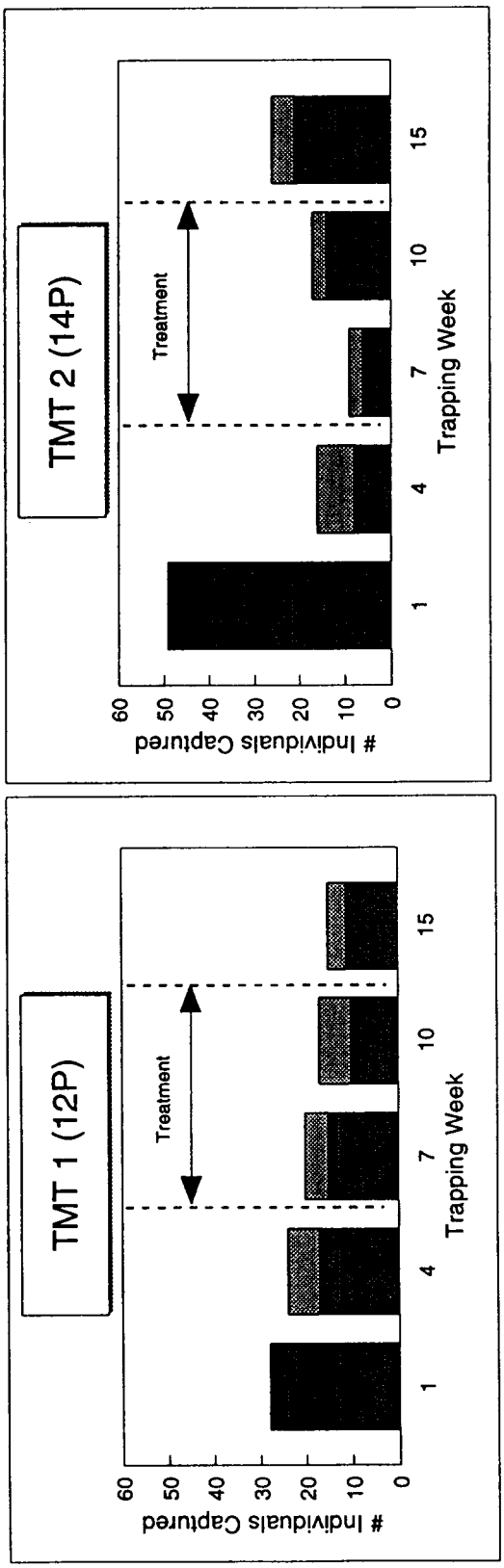
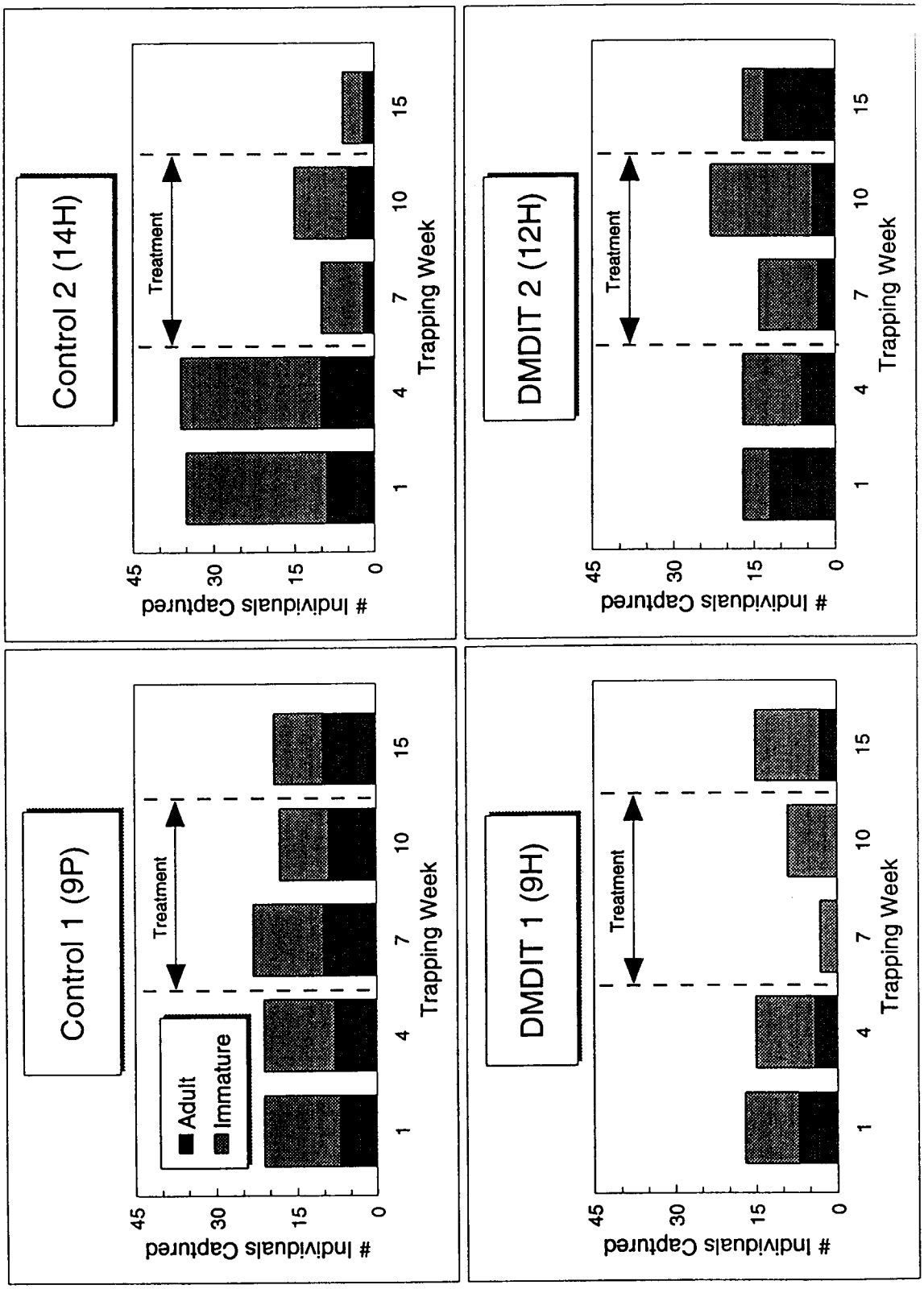


FIG. 1. Total number of roof rat captures and recaptures (numbers/300 trap nights) over five trapping weeks in session 1. Treatment period is indicated by vertical hatched lines and horizontal arrow.


Control 1 (9P)
Control 2 (14H)
DMDIT 1 (9H)
DMDIT 2 (12H)
Adult
Immature
Treatment
Individuals Captured
Trapping Week
0
15
30
45
1
4
7
10
15

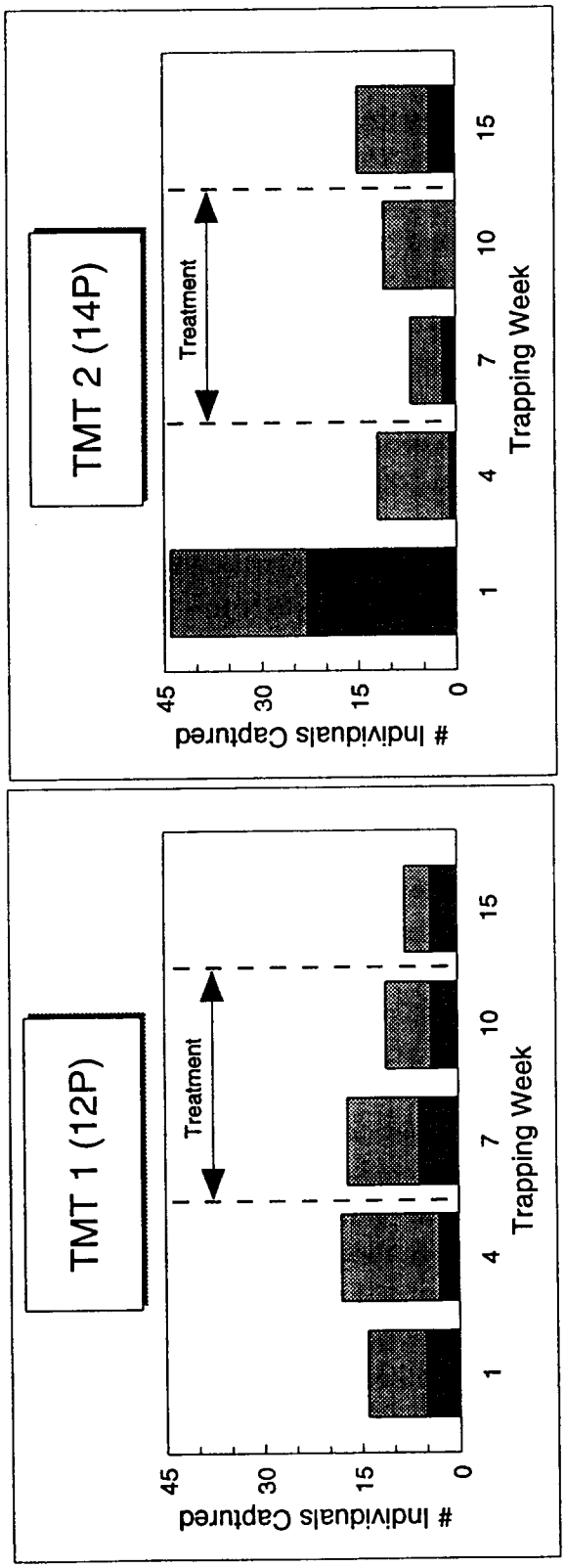


FIG. 2. Total number of individual male roof rats captured (numbers/300 trap nights) by age (all adults captured in breeding condition) in session 1. Treatment period indicated by vertical hatched bars and horizontal arrow.

week 1: $P = 0.69$, week 4: $P = 0.87$), during the treatment period (ANOVA, week 7: $P = 0.68$, week 10: $P = 0.48$) or during the posttreatment period (ANOVA, week 15: $P = 0.46$) (Table 1).

Mean maximum distances moved (MMDM) between consecutive trapping weeks are shown in Table 2. There were no significant differences in MMDM between treatments during pretreatment (ANOVA, $P = 0.77$) or following treatment application (ANOVA, week 4–7: $P = 0.69$, week 7–10: $P = 0.20$). Proportion of captures in traps within or adjacent to (within one adjacent tree) treated areas is displayed in Figure 3. Although capture numbers were quite low, the distribution of captures relative to the treated areas provided an indication of predator odor avoidance. Randomization testing detected no nonrandom differences in the proportion of captures within/adjacent to treated areas in pairwise comparisons of controls and DMDIT treatments (two-tailed, $P = 0.11$), controls and TMT treatments (two-tailed, $P = 0.85$), or DMDIT and TMT treatments (two-tailed, $P = 0.07$).

Telemetry. For all telemetry data, estimates were initially plotted for each animal for the duration of session 1. As rats displayed a high degree of individual variability in laboratory arena trials (Burwash et al., 1998), we felt it worthwhile to first display the results by individual. A consistent problem throughout session 1 was transmitter slippage or predation. Of the six rats initially collared on each grid, 0–3 rats per grid provided data throughout the entire session. Many of the radio-collared rats either had their transmitters recovered on the surface ($\sim 25\%$) (slip or predation), remained stationary underground ($\sim 15\%$) (slip or predation), or their signal was entirely absent ($\sim 5\%$) (transmitter failure or moved from grid >2 km). In one case a female rat lost her radio transmitter in the tree canopy two weeks after collaring. The radio transmitter was recovered ~ 5 m above the ground in working condition, with no signs of predation. One animal died from predation. This female weighed 120 g and was located during the first week following the initial DMDIT treatment application. The animal was first located in the canopy (19:00–21:00 hr), but in the subsequent location (21:01–23:00 hr), was observed on the surface running erratically. This activity appeared very unusual as rats were rarely observed on the ground in the orchard. In the final reading (23:01–01:00 hr) this individual was recovered on the surface missing half the lower body, with obvious signs of feral cat predation as evidenced by tooth puncture marks in the back of the neck and spine. To combine all individuals for each treatment would have yielded a widely varying sample size by week. It would also have been unreliable to use data from individuals not present throughout most of each session, as individual biases would not have been consistent across each telemetry week. Therefore, we decided to calculate average values only for those rats present throughout at least one pretreatment and one posttreatment (consecutive) telemetry week. In session 1 the number of rats (sample size) for all telemetry measurements was at least 3, except in

TABLE 1. MEAN MALE BODY WEIGHT OF ROOF RATS CAPTURED ON CONTROL, DMDIT, AND TMT TREATMENT GRIDS IN SESSION 1[a]

	Weight (g)									
	Pretreatment				Treatment				Posttreatment	
	Week 1		Week 4		Week 7		Week 10		Week 15	
Grids	Mean ± SE	*N*	Mean ± SE	*N*	Mean ± SE	*N*	Mean ± SE	*N*	Mean ± SE	*N*
Control										
9P	69 ± 10	21	70 ± 9	21	66 ± 6	23	77 ± 9	18	83 ± 11	19
14H	66 ± 8	35	67 ± 8	36	57 ± 10	10	67 ± 13	15	98 ± 35	4
DMDIT										
9H	76 ± 9	17	58 ± 9	15	34 ± 0	3	39 ± 2	9	59 ± 10	15
12H	102 ± 11	17	72 ± 12	17	57 ± 9	14	59 ± 7	23	108 ± 12	17
TMT										
12P	79 ± 16	14	55 ± 10	18	58 ± 9	17	81 ± 16	11	68 ± 18	8
14P	98 ± 8	44	47 ± 6	12	63 ± 14	7	39 ± 2	11	64 ± 12	15

[a]Values are mean weights with standard error (SE) and sample size (*N*); 9P, 14H, 9H, 12H, 12P, and 14P are grid names.

TABLE 2. MEAN MAXIMUM DISTANCE MOVED (MMDM) BETWEEN CONSECUTIVE TRAPPING WEEKS OF ROOF RATS CAPTURED ON CONTROL, DMDIT, AND TMT TREATMENT GRIDS IN SESSION 1[a]

	MMDM (m)					
	Pretreatment,		Treatment			
	week 1–4		Week 4–7		Week 7–10	
Grids	Mean ± SE	*N*	Mean ± SE	*N*	Mean ± SE	*N*
Control						
9P	10.8 ± 4.8	13	23.8 ± 6.5	13	17.4 ± 5.4	12
14H	30.4 ± 5.9	37	25.7 ± 7.1	25	28.9 ± 7.2	9
DMDIT						
9H	22.2 ± 4	19	20.9 ± 8	7	4.5 ± 4.5	3
12H	15.6 ± 3.6	18	23.7 ± 4.2	17	28.1 ± 5.6	13
TMT						
12P	17.6 ± 3.6	15	20.5 ± 6.1	13	10.3 ± 3.3	13
14P	27.5 ± 4.1	27	6.3 ± 3.1	11	8.3 ± 3.4	12

[a] MMDM is measured between first capture point in each of two successive trapping weeks. Standard error (SE) and sample size (*N*); 9P, 14H, 9H, 12H, 12P, and 14P are grid names.

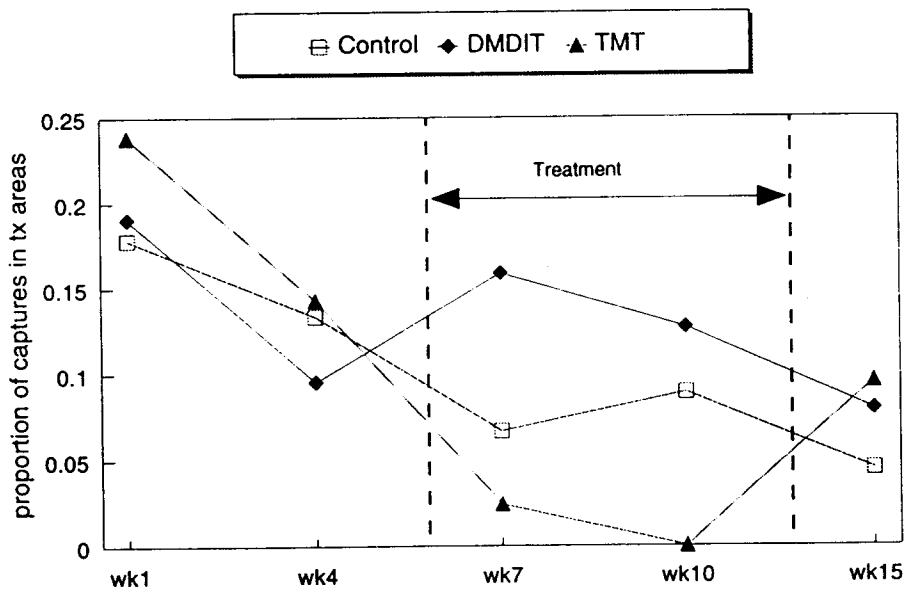


FIG. 3. Proportion of roof rat captures in traps within or adjacent (within 1 tree) to treated areas. Data are from session 1 mark–recapture and displayed by treatment type (defined in legend) by week. Treatment period indicated by vertical hatched lines and horizontal arrow.

pretreatment week 1 (not used in the analysis). For session 2, the number of rats (sample size) for all telemetry measurements was at least 7, except in the pretreatment week.

Session 1. The individual's weekly MCP home range estimates ranged from 63 m^2 to 4730 m^2 throughout session 1. The mean MCP home range estimates by telemetry week are displayed in Figure 4. A repeated measures ANOVA found no difference in treatments within or between weeks ($P = 0.61$). Median distance from the center of activity (MDIS) for individual roof rats ranged between 4 and 45 m. The mean MDIS estimates by telemetry week are displayed in Figure 5. Repeated measures ANOVA found no difference in treatments within or between weeks ($P = 0.45$). The proportion of telemetry readings in treated trees ranged between 0 and 85%. Mean estimates for proportion of

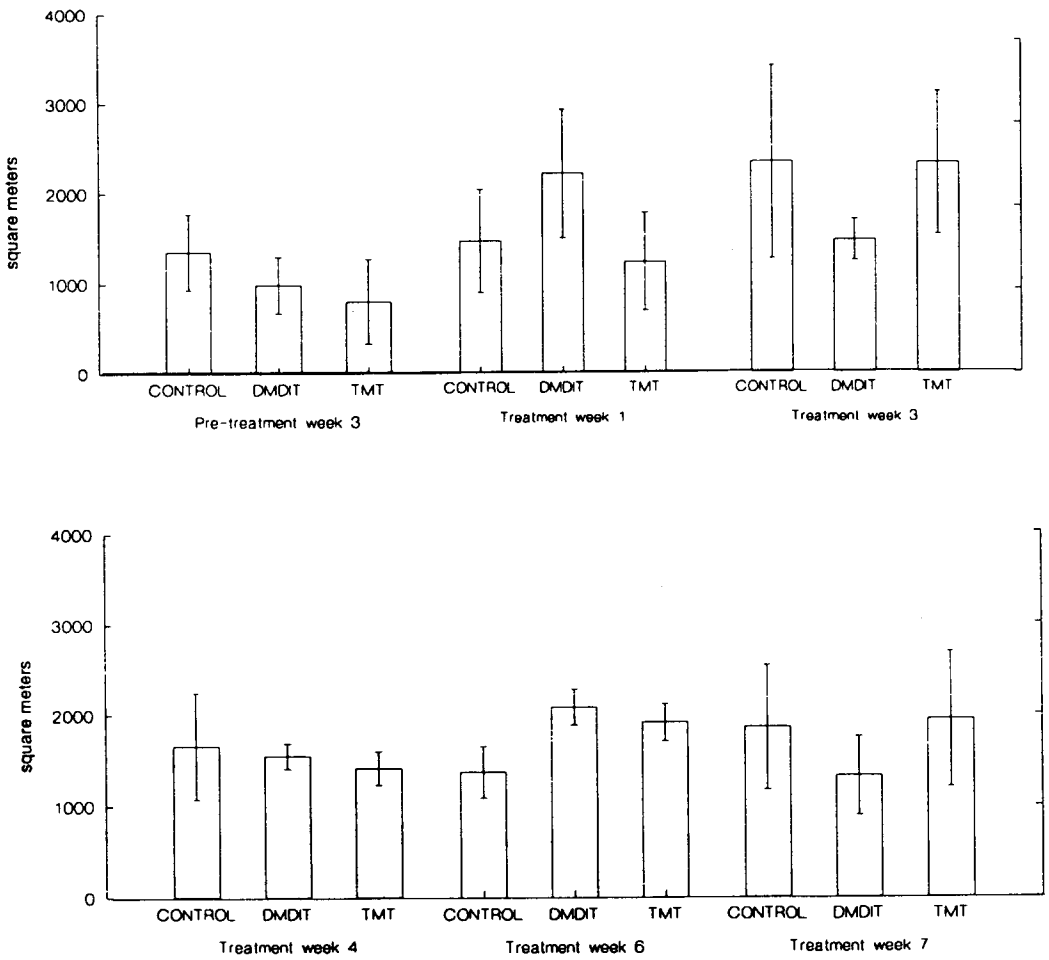


FIG. 4. Mean minimum convex polygon (MCP) estimates for three treatments (control, DMDIT, and TMT) by telemetry week during session 1 (June 15–August 31, 1994). Each value is the mean of at least three replicates ± standard error (SE).

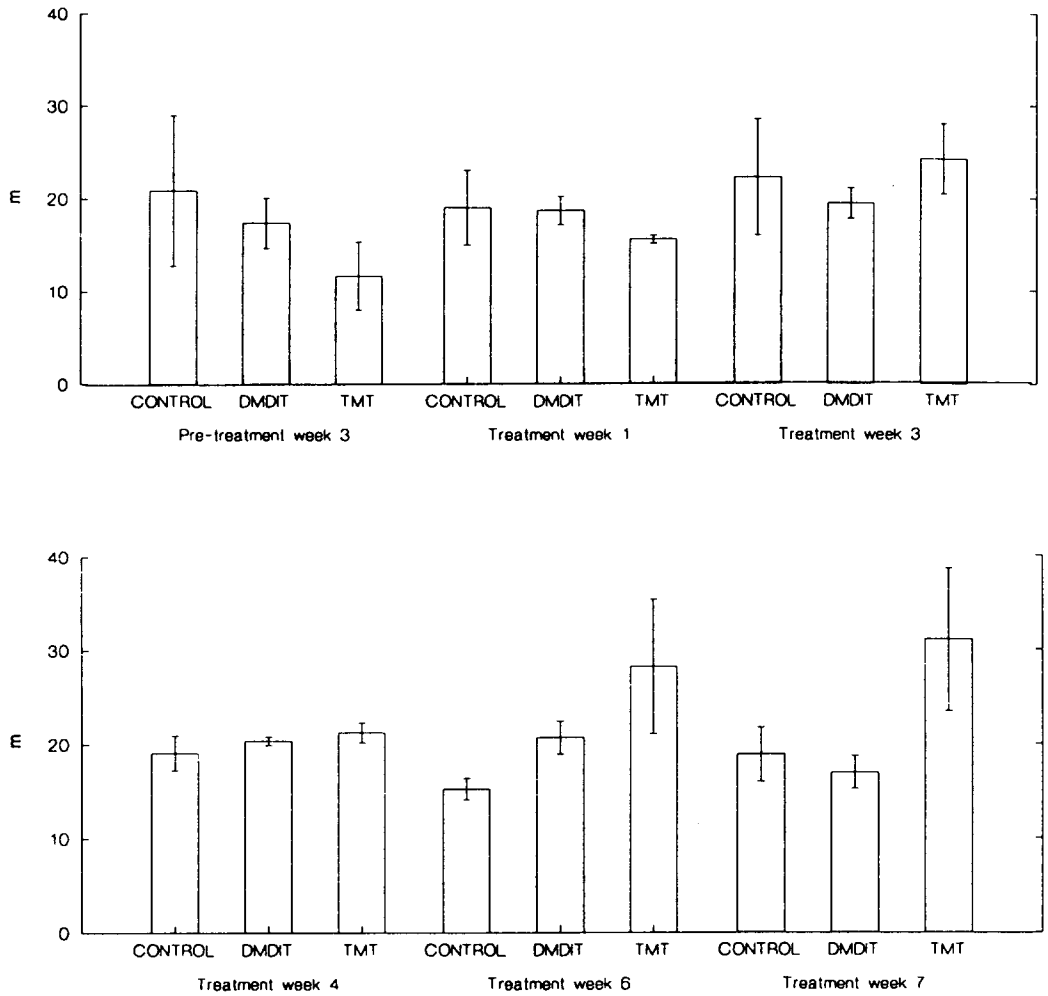


FIG. 5. Mean median distance traveled from center of activity (MDIS) estimates (meters) for three treatments (control, DMDIT, and TMT) by telemetry week during session 1 (June 15–August 31, 1994). Each value is the mean of at least three replicates ± standard error (SE).

telemetry locations in treated trees are displayed in Figure 6. Repeated-measures ANOVA revealed no difference in treatments within or between weeks ($P = 0.35$).

Session 2. The individual's weekly minimum convex polygon (MCP) home range estimates ranged from 125 m^2 to 12,162 m^2 throughout session 2. The mean MCP home range estimates for roof rats in session 2, treatment 1, are displayed in Figure 7. Repeated-measures ANOVA found no difference in treatments within or between weeks ($P = 0.54$). Mean MCP home range estimates for roof rats in session 2, treatment 2, are displayed in Figure 8. Repeated-

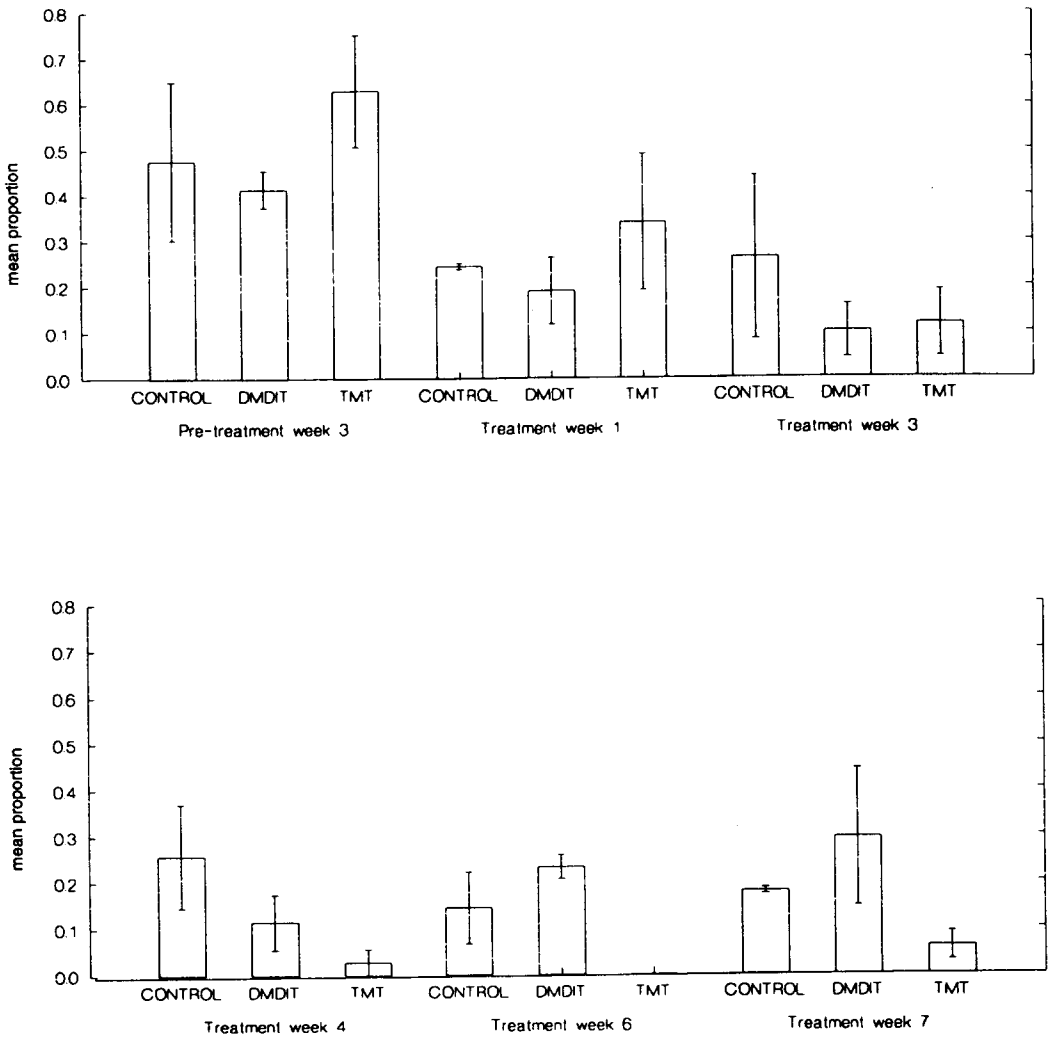


FIG. 6. Mean proportion of telemetry readings in treated trees for three treatments (control, DMDIT, and TMT) by telemetry week during session 1 (June 15–August 31, 1994). Each value is the mean of at least three replicates ± standard error (SE).

measures ANOVA found no difference in treatments within or between weeks ($P = 0.08$).

For individual rats, median distance from center of activity (MDIS) ranged from 5 to 60 m. No trends in groups of individuals were obvious from these data. Mean MDIS values for roof rats present throughout session 2, treatment 1, ranged from 16 to 26 m. No differences within or between treatment weeks were determined ($P = 0.34$). For session 2, treatment 2, mean MDIS values ranged from 14 to 23 m, and no significant differences were found ($P = 0.19$).

For individuals present throughout session 2, treatment 1, the mean pro-

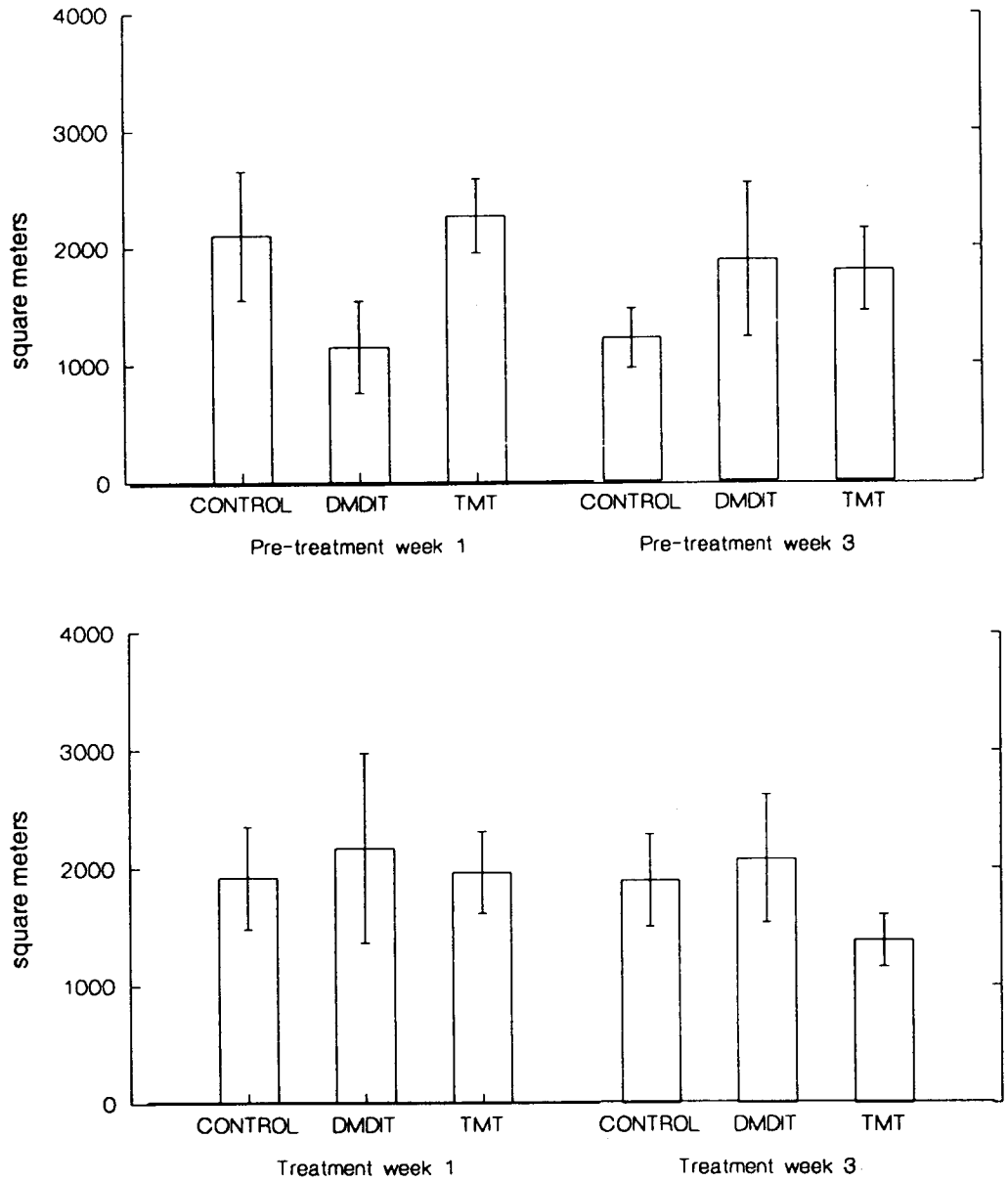


FIG. 7. Mean minimum convex polygon (MCP) estimates for three treatments (control, DMDIT, and TMT) by telemetry week during session 2, treatment 1 (September 20–November 4, 1994). Each value is the mean of at least seven replicates ± standard error (SE).

portion of readings in treated trees ranged from 25 to 57% (Figure 9). No significant differences were found within or between treatment weeks ($P = 0.53$). In session 2, treatment 2, the mean proportion of locations in treated trees ranged from 20 to 77% (Figure 10). Again, there were no significant differences found within or between treatment weeks ($P = 0.12$).

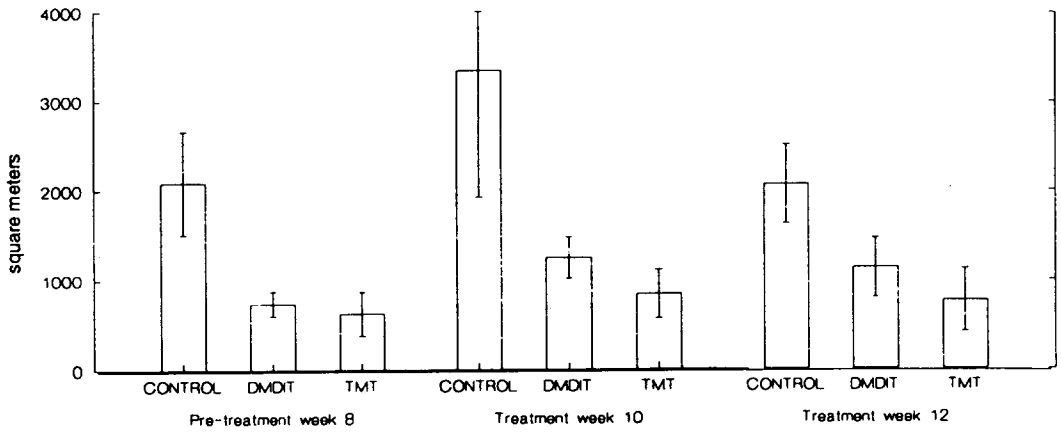


FIG. 8. Mean minimum convex polygon (MCP) estimates for three treatments (control, DMDIT, and TMT) by telemetry week during session 2, treatment 2 (November 9–December 10, 1994). Each value is the mean of at least seven replicates ± standard error (SE).

DISCUSSION

A concern throughout this study was the individual variability displayed by the roof rat. Ideally one could reduce this variability by increasing the sample size and number of replicates. However, the results from Burwash et al. (1998) suggested that two predator odor treatments should be field-tested, which limited the experimental design to two replicates for each of three treatments.

Variable capture rates indicated cautious interpretation of population parameters. However, some of the population parameters based on mark–recapture information provided worthwhile data as to changes in the trapped population. Many other small mammal population studies have recognized variable trappability when interpreting mark–recapture results (Sullivan, 1990, 1994; Nichols and Pollock, 1983).

Telemetry data were also subject to the effects of small sample sizes with a low number of replicates. Predation, radio-collar slippage, and malfunction all contributed to the small sample sizes of animals, especially towards the end of session 1. Although sample sizes were quite small, the specific individual results from the telemetry analysis provided useful insight into patterns of habitat use.

Poor capture success in live trap studies with rats is common (Worth, 1950; Kartman and Lonergan, 1955; Lindsey et al., 1973; Chin, 1983). Rats become trap-shy following initial capture (Lindsey et al., 1973; Spencer and Davis, 1950) while juvenile rats become trap-happy (Nichols and Pollock, 1983). With these concerns in mind, we used a mark–recapture design based on an earlier successful pilot study. An important technique in this procedure was to prebait

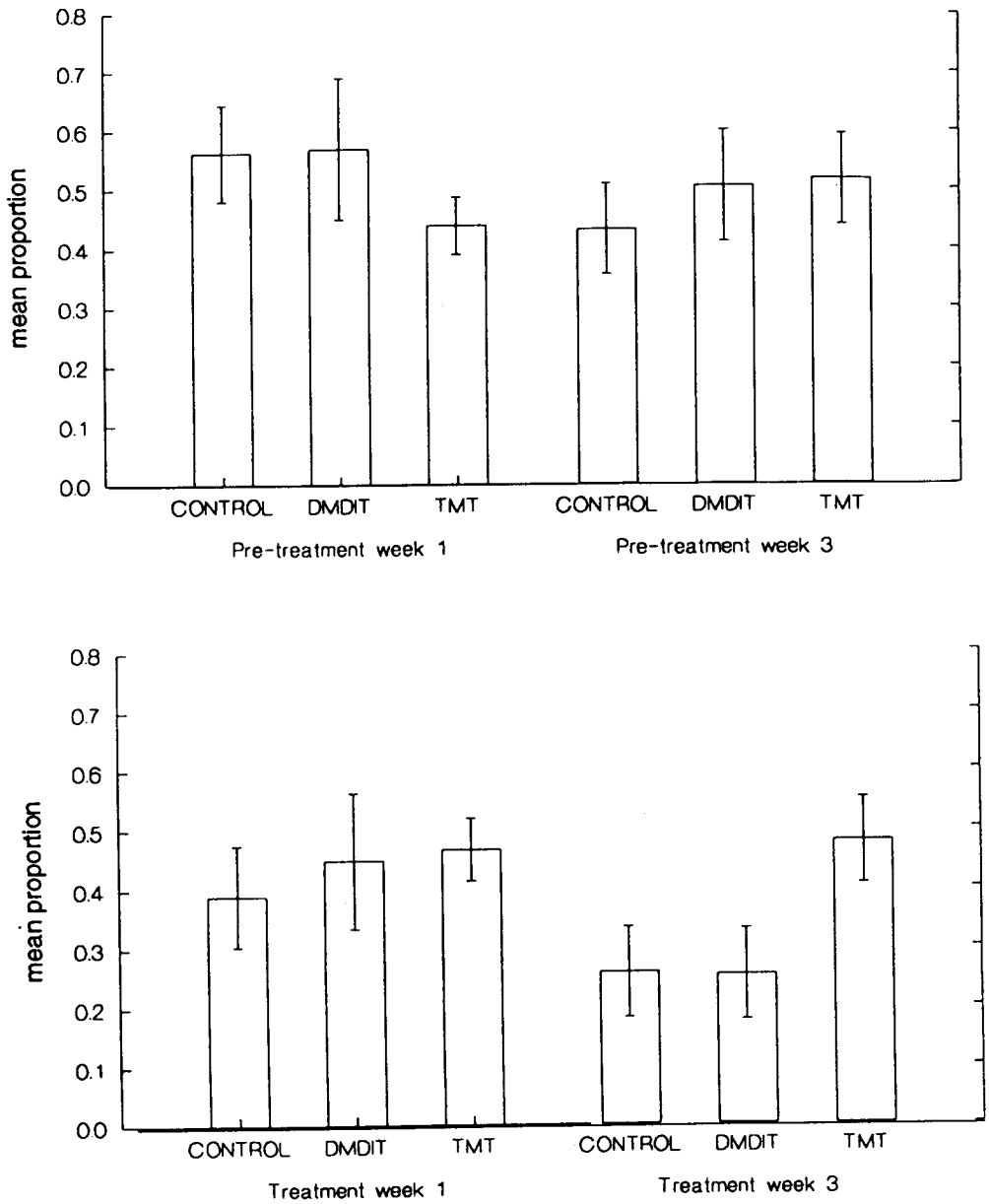


FIG. 9. Mean proportion of telemetry readings in treated trees for three treatments (control, DMDIT, and TMT) by telemetry week during session 2, treatment 1 (September 20–November 4, 1994). Each value is the mean of at least three replicates ± standard error (SE).

traps (locked open) starting four days prior to each trapping week. This should have reduced neophobic responses to the traps and to recapture. The methodology used for the pilot study followed small mammal mark–recapture studies in North America (Sullivan, 1990; Ransome and Sullivan, 1997). We also fol-

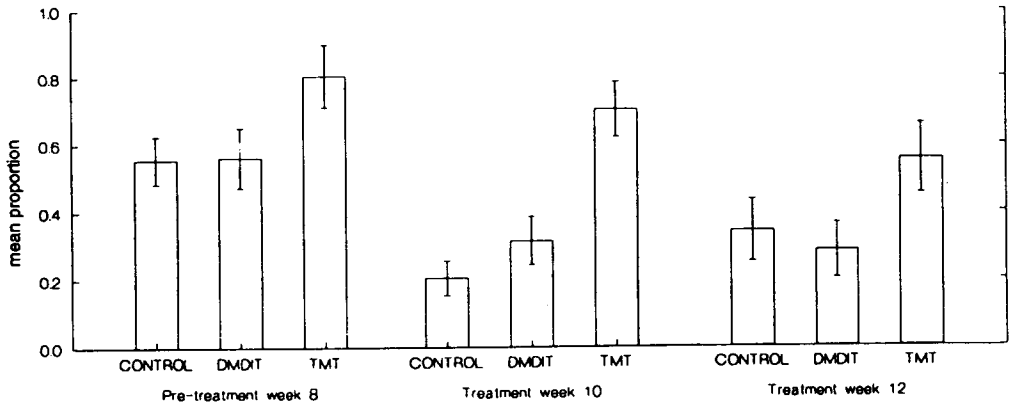


FIG. 10. Mean proportion of telemetry readings in treated trees for three treatments (control, DMDIT, and TMT) by telemetry week during session 2, treatment 2 (November 9–December 10, 1994). Each value is the mean of at least three replicates ± standard error (SE).

lowed standard operating procedures utilized by the National Wildlife Research Center (NWRC) to live-trap rodents in the orchard.

Comparisons between actual capture numbers (relative density) resulted in no significant effect of treatments on numbers of rats. Although capture numbers varied greatly, some useful information regarding the composition of these captures was gained. Because female breeding condition was more difficult to assess and weights fluctuated with pregnancy status, only males were considered for evaluation of breeding condition and body weight. The number of breeding males was not statistically different between treatment grids or between treatment weeks.

Mean male body weights did not vary within or between treatment weeks. Most of the declining trend in mean weights can be attributed to a greater proportion of juveniles being captured in weeks subsequent to the initial trapping week. Survival rate estimates were not tested because of low trappability estimates and the relatively short mark–recapture sampling period. Thus, we cannot accept hypothesis 1: reduction in number, incidence of breeding, and body weights of rats in predator-odor treated areas.

Previous mark–recapture studies with predator odors and small mammals have indicated movement of animals from treated areas (Sullivan and Crump, 1986; Sullivan et al., 1988a, b). In this study, the treated areas were in patches within the trapping grid, thereby resulting in an uneven distribution of treatment. The MMDM did not differ between treatments or between treatment weeks. MDIS telemetry data for session 1, although not statistically significant, indicated a trend of increasing values on the TMT grids. However, this trend was not observed with the session 2 telemetry data. Hypothesis 2, that predator odor

treatments would increase the distance traveled from an individual's center of activity, was not supported by our results.

Individual home range estimates varied greatly for both telemetry sessions. Hypothesis 3, that roof rat home range estimates will increase following predator odor treatment application, was not supported by our results. Although not assessed, MDIS and MCP estimates are probably highly correlated, as determined in a previous study in the same orchard (Tobin et al., 1996). Plotting individual locations by treatment week indicated that home range locations tended to shift slightly by week.

The mark–recapture results indicated that the proportion of captures in traps within or adjacent to treated trees tended to decrease over the treatment period on the TMT grids, but not significantly. This trend was also observed with the session 1 telemetry data (lower number of locations in treated areas), although statistical differences were not detected. However, the telemetry results from session 2 do not indicate any treatment differences. Therefore, our results do not support hypothesis 4 of a lower number of locations in trees treated with predator odors.

Throughout the entire study, none of the radio-collared rats traveled more than ~150 m from its original weekly home range location. This indicates that no rat ever left the grid on which it was originally trapped. The few rats that did travel greater than this distance either had their radio collar recovered (predation/slippage) or remained stationary underground, which is also likely to have resulted from predation. The live-trapping data also confirmed small home ranges, as no animal tagged on one grid was ever captured on any other grid. These results support similar findings showing that rats do not stray far from their home range (Spencer and Davis, 1950; Worth, 1950; Pippin, 1961; Tobin et al., 1996).

A potential explanation for this observation is the high abundance of year-round food coupled with a high density of individuals. Population density of roof rats has been associated with food availability in the Galapagos Islands (Clark, 1980), but this should not be a limiting factor in the orchard habitat. Rodents residing in the orchard have an almost continuous availability of nuts due to the prolonged flowering season and extended nut maturation period in Hawaii (Cavaletto, 1983). Studies have revealed that the roof rat's diet in orchards consists almost entirely of macadamia nuts, which allows rats to breed on a year-round basis (Tobin et al., 1993).

We found no differences in roof rat responses to DMDIT and TMT semiochemical treatments. A lack of response to the predator odor treatments may be a result of important habitat values present in the macadamia orchard: abundance of food, water, and cover. Other small mammal studies have demonstrated that cover is an important factor in the presence of predator odor (Merkens

et al., 1991). The lack of response may also be attributed to improper methodology to detect the response or low effectiveness of odor-release devices. Another potential explanation may be roof rat habituation to the odors or a lack of recognition of the semiochemicals, which were based on predator species not established in Hawaii. Although some studies indicate genetic recognition of odors (Gorman, 1984; Vernet-Maury et al., 1984, Boag and Mlotkiewicz, 1994), this theory is difficult to test, and perhaps learned behavior is more of a factor in this case. The roof rat's resilient nature probably allows for this adaptability, and many studies have reported its ability to learn new behaviors (Berdoy and MacDonald, 1991; Galef and Whiskin, 1994).

Methodology changes in future research into predator odor effects on roof rats should include a mark–recapture design with intensive sampling over a short period of time with longer intervals between sampling, and use of closed population analysis techniques. These closed population techniques have models that can allow for unequal capture probabilities, as occurred in this study. A more intensive sampling design (e.g., every two weeks) than used in our study may increase susceptibility to capture and allow use of open population analysis techniques.

Telemetry techniques should continue to be utilized as they provide specific information on individual movements. An important telemetry measurement to consider is that of shifts in center of activity. This could have been occurring in this study and may not have been properly addressed in the home range estimates and proportion of readings in treated trees.

For future studies, the importance of cover should also be explored through cover manipulation experiments coupled with mark–recapture and/or telemetry techniques. In addition, studies should focus on a population of rats that is well understood with respect to population parameters and movement patterns, with a treatment design maximizing the number of replicates. Whereas our results did not indicate semiochemical avoidance, recent findings with roof rat avoidance of mongoose feces in the field (Tobin et al., 1995) imply that potential responses may exist. Although semiochemicals from mongoose feces were not available at the time of this study, further research into the roof rat's response to this predator odor is recommended based on the laboratory findings of Burwash et al. (1998) and recent field results (Tobin et al., 1997).

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REFERENCES

ATKINSON, I. A. E. 1985. The spread of the commensal species of *Rattus* to oceanic islands and their effects on island avifauna. International Council for Bird Preservation Technical Publication 3, pp. 35–84.

BERDOY, M., and MACDONALD, D. W. 1991. Factors affecting feeding in wild rats. *Acta Ecol.* 12(2):261–279.

BOAG, B., and MLOTKIEWICZ, J. A. 1994. Effect of odor derived from lion feces on behavior of wild rabbits. *J. Chem. Ecol.* 20:631–637.

BUCKLE, A. P., and FENN, M. G. P. 1992. Rodent control in the conservation of endangered species, pp. 36–41, *in* J. E. Borrecco and R. E. Marsh (eds.). Proceedings, 15th Vertebrate Pest Conference. University of California, Davis.

BURWASH, M. D., TOBIN, M. E., WOOLHOUSE, A. D., and SULLIVAN, T. P. 1998. Laboratory evaluation of predator odors for eliciting an avoidance response in roof rats (*Rattus rattus*), *J. Chem. Ecol.* 24:49–66.

CARPENTER, S. R., FROST, T. M., HEISEY, D., and KRATZ, T. K. 1989. Randomized intervention analysis and the interpretation of whole-ecosystem experiments. *Ecology* 70:1142–1152.

CAVALETTO, C. G. 1983. Macadamia nuts, pp. 361–379, *in* H. T. Chan Jr. (ed.). Handbook of Tropical Foods. Marcel Dekker, New York.

CHIN, M. 1983. Home range and abundance of black rats in citrus groves, Madera County, California. MA thesis. Department of Biology, California State University, Fresno, 111 pp.

CLARK, D. B. 1980. Population ecology of *Rattus rattus* across a desert-montane forest gradient in the Galapagos Islands. *Ecology* 61:1422–1433.

GALEF, B. G., JR., and WHISKIN, E. E. 1994. Passage of time reduces effects of familiarity on social learning: Functional implications. *Anim. Behav.* 48:1057–1062.

GORMAN, M. L. 1984. The response of prey to stoat (*Mustela erminea*) scent. *J. Zool. London* 202:419–423.

KARTMAN, L., and LONERGAN, R. P. 1955. Observations on rats in an enzootic plague region of Hawaii. Public Health Report, Communicable Disease Center Hawaiian Field Station.

KREBS, C. J. 1966. Demographic changes in fluctuating populations of *Microtus californicus. Ecol. Monogr.* 36:239–273.

LINDSEY, G. D., NASS, R. D., HOOD, G. A., and HIRATA, D. N. 1973. Movement patterns of Polynesian rats (*Rattus exulans*) in sugarcane. *Pac. Sci.* 27:239–246.

LUND, M. 1994. Commensal rodents, pp. 23–43, *in* A. P. Buckle and R. H. Smith (eds.). Rodent Pests and their Control. CAB International, Wallingford, UK.

MANLY, B. F. J. 1990. Randomization and Monte Carlo Methods in Biology. Chapman & Hall, New York.

MERKENS, M., HARESTAD, A. S., and SULLIVAN, T. P. 1991. Cover and efficacy of predator-based repellents for Townsend's vole, *Microtus townsendii. J. Chem. Ecol.* 17:401–412.

NICHOLS, J. D., and POLLOCK, K. H. 1983. Estimation methodology in contemporary small mammal capture–recapture studies. *J. Mammal.* 64:253–260.

PIPPIN, W. F. 1961. The distribution and movement of roof rats on Mona Island, West Indies. *J. Mammal.* 42:344–348.

PRAKASH, I. 1988. Bait shyness and poison aversion, pp. 321–329 *in* I. Prakash (ed.). Rodent Pest Management. CRC Press, Boca Raton, Florida.

RANSOME, D. B., and SULLIVAN, T. P. 1997. Food limitation and habitat preference of *Glaucomys sabrinus* and *Tamiasciurus hudsonicus. J. Mammal.* 78:538–549.

RITCHIE, C., and SULLIVAN, T. P. 1989. Monitoring methodology for assessing the impact of forest herbicide use on small mammal populations in British Columbia. British Columbia Ministry of Forests, FRDA Report 081, 23 pp.

SAVILLE, D. J. 1990. Multiple comparison procedures: The practical solution. *Am. Stat.* 44:174–180.

SPENCER, H. J., and DAVIS, D. E. 1950. Movement and survival of rats in Hawaii. *J. Mammal.* 31:154–157.

STONE, C. P. 1985. Alien animals in Hawaii's native ecosystems: toward controlling the adverse effects, pp. 251–297, *in* C. P. Stone and J. M. Scott (eds.). Hawaii's Terrestrial Ecosystems: Preservation and Management. Cooperative National Park Resources Studies Unit, Honolulu.

STUWE, M., and BLOHOWIAK, C. E. 1989. McPaal micro-computer programs for the analysis of animal locations. Conservation and Research Center, National Zoological Park, Smithsonian Institution.

SUGIHARA, R. T., TOBIN, M. E., and KOEHLER, A. E. 1995. Zinc phosphide baits and prebaiting for controlling rats in Hawaiian sugarcane. *J. Wildl. Manage.* 59:882–889.

SULLIVAN, T. P. 1990. Responses of red squirrel (*Tamiasciurus hudsonicus*) populations to supplemental food. *J. Mammal.* 71:579–590.

SULLIVAN, T. P. 1994. Influence of herbicide-induced habitat alteration on vegetation and snowshoe hare populations in sub-boreal spruce forest. *J. Appl. Ecol.* 31:717–730.

SULLIVAN, T. P., and CRUMP, D. R. 1986. Avoidance response of pocket gophers (*Thomomys talpoides*) to mustelid anal gland compounds, pp. 519–531, *in* D. Duvall, D. Müller-Schwarze, and R. M. Silverstein (eds.). Chemical Signals in Vertebrates IV. Plenum Press, New York.

SULLIVAN, T. P., CRUMP, D. R., and SULLIVAN, D. S. 1988a. The use of predator odor repellents to reduce feeding damage by herbivores. III. Montane and meadow voles (*Microtus montanus* and *Microtus pennsylvanicus*). *J. Chem. Ecol.* 14:363–377.

SULLIVAN, T. P., CRUMP, D. R., and SULLIVAN, D. S. 1988b. The use of predator odor repellents to reduce feeding damage by herbivores. IV. Northern pocket gophers (*Thomomys talpoides*). *J. Chem. Ecol.* 14:379–389.

SULLIVAN, T. P., SULLIVAN, D. S., CRUMP, D. R., WEISER, H., and DIXON, E. A. 1988c. Predator odors and their potential role in managing pest rodents and rabbits, pp. 272–276, *in* J. E. Borrecco and R. E. Marsh, (eds.). Proceedings, 15th Vertebrate Pest Conference. University of California, Davis.

SULLIVAN, T. P., CRUMP, D. R., WIESER, H., and DIXON, E. A. 1990. Comparison of release devices for stoat (*Mustela erminea*) semiochemicals used as montane vole (*Microtus montanus*) repellents. *J. Chem. Ecol.* 16:951–957.

TOBIN, M. E. 1992. Rodent damage in Hawaiian macadamia orchards, pp. 272–276, *in* J. E. Borrecco and R. E. Marsh, (eds.). Proceedings, 15th Vertebrate Pest Conference. University of California, Davis.

TOBIN, M. E., SUGIHARA, R. T., and OTA, A. K. 1990. Rodent damage to Hawaiian sugarcane, pp. 120–123, *in* L. R. Davis and R. E. Marsh (eds.). Proceedings, 14th Vertebrate Pest Conference. University of California, Davis.

TOBIN, M. E., KOEHLER, A. E., SUGIHARA, R. T., UEUNTEN, G., and YAMAGUCHI, A. M. 1993. Effects of trapping on rat populations and subsequent damage and yields of macadamia nuts. *Crop Prot.* 12:243–248.

TOBIN, M. E., ENGEMAN, R. M., and SUGIHARA, R. T. 1995. Effects of mongoose odors on rat capture success. *J. Chem. Ecol.* 21:635–639.

TOBIN, M. E., SUGIHARA, R. T., KOEHLER, A. E., and UEUNTEN, G. R. 1996. Seasonal comparison of *Rattus rattus* (Rodentia, Muridae) in a Hawaiian macadamia nut orchard. *Mammalia* 60:3–13.

TOBIN, M. E., KOEHLER, A. E., SUGIHARA, R. T., and BURWASH, M. D. 1997. Repellency of mongoose feces and urine to rats (*Rattus* spp.). *in* R. Mason and D. Nolte (eds.). Proceedings of the Repellents Symposium. National Wildlife Research Center, USDA-APHIS, Denver, Colorado (In press).

TOMICH, P. Q. 1986. Mammals in Hawaii, 2nd ed. Bishop Museum Press, Honolulu, 375 pp.

VERNET-MAURY, E., POLAK, E. H., and DEMAEL, A. 1984. Structure-activity relationship of stress-inducing odorants in the rat. *J. Chem. Ecol.* 10:1007-1018.

VERNET-MAURY, E., CONSTANT, B., and CHANEL, J. 1992. Repellent effect of trimethyl thiazoline in the wild rat *Rattus norvegicus* Berkenhout, pp. 305-310, *in* R. L. Doty and D. Müller-Schwarze (eds.). Chemical Signals in Vertebrates VI. Plenum Press, New York.

WORTH, C. B. 1950. Field and laboratory observations on roof rats, *Rattus rattus* (Linnaeus), in Florida. *J. Mammal.* 31(3):293-304.